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Learning to Drink Beer by Mistake

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Learning to Drink Beer by Mistake

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Abstract: This paper considers the possibility of using adaptive learning and mistakes to select a unique equilibrium in signaling games. It is assumed that players are boundedly rational in that they use an adaptive rule to update their beliefs. Moreover, they sometimes make mistakes and choose an action at random. By computer simulation it is shown that, when players do not make mistakes, the equilibrium selected depends on the initial distribution of beliefs. When the probability of mistakes is positive the learning dynamics selects for Kohlberg-Mertens' stability concept.

Introduction

This paper considers the possibility of using adaptive learning and mistakes to select a unique equilibrium in extensive form games with incomplete information. The simplest class of games with incomplete information is that of signaling games (see next section). They have been widely used in economics (e.g. Spence, 1974; Grossman, 1981; Kreps-Wilson, 1982b; Milgrom-Roberts, 1982 and 1986). Typically, signaling games have multiple (sequential) equilibria. The approach followed in the literature to reduce this multiplicity has been to impose restrictions on out-of-equilibrium beliefs. Cho-Kreps (1987) and Banks-Sobel (1987) analyze the power of strategic stability (Kohlberg-Mertens, 1986) to select among equilibria in signaling games.

Here a different approach is followed. It is assumed that players are boundedly rational in that they use an adaptive rule to update their beliefs. Moreover, they sometime make mistakes and choose an action at random.

By computer simulations it is shown that, when players do not make mistakes, the equilibrium selected depends on the initial distribution of beliefs. When the probability of mistakes is positive the learning dynamics selects for strategic stability. This is similar to Fudenberg-Kreps (1988). In their model players are boundedly rational and deviations are the result of conscious experimentation by the players. They claim¹ that by imposing restrictions on players' experimentation procedures refinements of sequential equilibrium can be justified.

The remaining of this paper is organized as follows: the next section introduces signaling games; section 2 considers an example; the model is presented in section 3 and in section 4 the results of the simulations are illustrated; section 5 concludes.

1 Signaling Games²

Consider a *signaling game* between two players: the sender (S) and the receiver (R). Nature moves first, selecting one of a finite number of possible types for player S according to a strictly positive probability distribution $\mathbf{p} = \{p(t) > 0 \text{ for all types } t \in T \text{ and } \sum_{t \in T} p(t) = 1\}$ which is common knowledge among the players. Player S is informed of nature's choice and sends to player

¹In Fudenberg-Kreps, draft 0.11-July 1988, this is still a claim since no proof is given.

²For an introduction to signaling games see ch.8 of Fudenberg-Tirole (1991); for more advanced material see ch.11 of the same book.

R an observable message m (the signal), chosen from the finite set M . The receiver then takes an action a , from the finite set A , in response to m without knowing the sender's type but knowing p . After the game is over S gets a payoff $u_S(t, m, a)$ and R gets $u_R(t, m, a)$. A strategy for S is a signaling rule $m(t)$ which maps T into M (or into a probability distribution over M if mixed strategies are allowed). A strategy for R is an action rule $a(m)$ which maps M into A (or into a probability distribution over A if mixed strategies are allowed) ³.

In a signaling game an equilibrium must specify not only the best strategy for each player but also players' beliefs at each information set, including information sets off-the-equilibrium path (i.e. information sets that have zero probability in equilibrium).

A *sequential equilibrium* ⁴ consists of a signaling rule $m^*(t)$ for S , an action rule $a^*(m)$ for R and beliefs $\mu(\cdot/m)$ such that:

- (i) $m^*(t) \in \arg\max u_S(t, m, a^*(m))$;
- (ii) $a^*(m) \in \arg\max \sum_{t \in T} u_R(t, m, a) \mu(t/m)$;
- (iii) $\mu(t/m)$ is computed from $p(t)$, m and $m^*(t)$ using Bayes' rule, whenever applicable ⁵.

In words, (i) states that $m^*(t)$ maximizes S 's expected utility given R 's equilibrium strategy; (ii) states that $a^*(m)$ maximizes R 's expected utility given his posterior beliefs $\mu(\cdot)$; (iii) states that, after messages whose prior probability is positive, R 's beliefs are updated using Bayes' rule. After *unexpected* messages arbitrary posterior beliefs are allowed.

³We can write

$$m(t) = \{m: p_S(m/t) > 0 \text{ and } \sum_{m \in M} p_S(m/t) = 1 \quad \forall t\}$$

and

$$a(m) = \{a: p_R(a/m) > 0 \text{ and } \sum_{a \in A} p_R(a/m) = 1 \quad \forall m\}$$

where $p_S(m/t)$ is the probability that S sends m given that his type is t and $p_R(a/m)$ is the probability that R chooses a after having received m .

⁴For signaling games the sets of sequential equilibria and Perfect Bayesian Equilibria coincide (Fudenberg-Tirole, 1991 p.346).

⁵That is:

$$\mu(t/m) = \frac{p(t)p_S(m/t)}{\sum_{t' \in T} p(t')p_S(m/t')}$$

whenever $\sum_{t' \in T} p(t')p_S(m/t') > 0$

In a signaling game there may be multiple sequential equilibria ⁶. It is often the case that some are justified by more *plausible* beliefs than others. Accordingly, the refinement approach has tried to reduce the set of sequential equilibria by excluding *unplausible* beliefs.

Cho-Kreps's (1987) refinement of sequential equilibrium (which they call the *Intuitive Criterion*) is based on *equilibrium dominance* and says that the receiver believes that an out-of-equilibrium message can only be sent by a type who can *reasonably* hope to gain from the deviation. Formally, let $J(m)$ be the set of types who get less than their equilibrium payoff by choosing an out-of-equilibrium message m , provided R plays an undominated strategy: $J(m) = \{t \text{ s.t. } u_s^*(t) > u_s(t, m, a^*(m))\}$. The equilibrium under consideration satisfies the Intuitive Criterion if, for any out-of-equilibrium message m , there is no type t' such that:

$$u^*(t') < \min_{a \in BR(T/J(m), m)} u_s(t', m, a^*(m))$$

$$\text{where } BR(T/J(m), m) = \argmax_{t \in T/J(m)} \sum u_R(t, a, a) \mu(t/m)$$

Note the central role given by this criterion to the equilibrium under consideration, that is utility is confronted with the utility obtained in the given equilibrium.

A stronger criterion is *divinity* (Bank-Sobel, 1987) according to which it is less likely that one type of sender has deviated in a particular fashion than another type, if any response by the receiver that makes the first type willing to deviate makes also the second type willing to deviate ⁷.

The above mentioned criteria are both implied by Kohlberg-Mertens' stability concept. A subset M of the Nash equilibria of a given game G is said to be *stable* if for any $\epsilon > 0$ there is a $\delta > 0$ such that every game G' that is within δ of G ⁸, has some Nash equilibrium that is less than ϵ distant

⁶Some differ only for the inference they allow the receiver to make when observing out-of-equilibrium signals; others also for the final outcome.

⁷For a formal treatment of *divinity* and the related criterion of *universal divinity* see the original paper by Bank-Sobel or Fudenberg-Tirole (1991).

⁸More precisely, for any completely mixed strategy vector ρ_s, ρ_R and for any δ_s, δ_R ($0 < \delta_i < \delta$ $i = S, R$) every strategy s_i in G is replaced by $(1 - \delta_i)s_i + \delta_i \rho_i$ in G' .

(according to a predefined metric) from the set M . This means that, for any small perturbation of the strategy set that induces the players to play completely mixed strategies, there is an equilibrium "near" the set M . Strategic stability is a set-valued concept; that is, a solution is a set of *connected components*⁹.

For our purpose the following two results of Kohlberg-Mertens are relevant:

P1: *There exists a stable set which is contained in a single connected component of the set of Nash equilibria and every generic tree has a stable payoff* (i.e. a payoff obtained in every equilibrium of a stable set).

P2: *A stable set contains a stable set of any game obtained by deletion of a strategy which is an inferior response in all the equilibria of the set.*

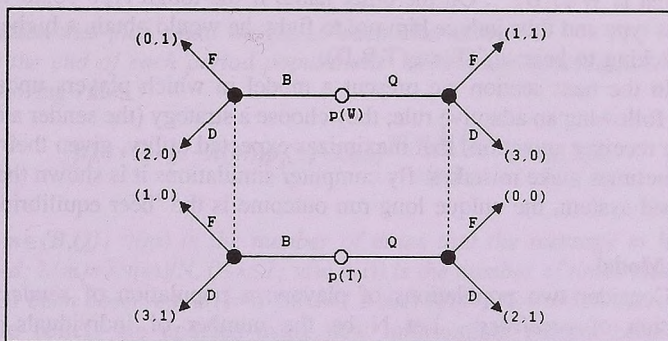
The first proposition states that a stable set exists and that stability is a refinement of Nash equilibrium. Moreover, since the stable set is contained in the set of *divine* equilibria which in turn is contained in the set of equilibria satisfying the Intuitive Criterion¹⁰, **P1** ensures existence of them all. The second proposition captures the forward induction argument according to which past actions should be interpreted as signals of future intentions (even though those actions may not influence payoffs in the continuation game). Accordingly, strategies that are never a (weak) best response to any of the opponent's strategy profiles in the component under consideration can be eliminated.

2 The 'Beer-Quiche' Game

A famous signaling game, known in the literature as the 'Beer-Quiche' game (Cho-Kreps, 1987), is the following: player S is one of two types: weak (W) with probability $p(W)$ or tough (T) with probability $p(T)$. He sends a signal to player R by choosing beer (B) or quiche (Q) for breakfast. The weak type of player S prefers quiche; the tough, beer. After having received the signal, player R decides whether to fight or not; he prefers to fight (F) if S is weak but he would rather not (D) if S is tough. Whether weak or tough, S prefers not to fight and he would rather have his least preferred breakfast than fight. The extensive form representation of the Beer-Quiche game is shown below:

⁹Intuitively, a connected set is such that any two points in the set can be joined by a path itself belonging to the set.

¹⁰See Cho-Kreps (1987).



The game has two sequential equilibria in pure strategies ¹¹. In the first, the 'beer equilibrium', the sender has beer for breakfast regardless of his type and the receiver replies F to Q and D to B. In the second, the 'quiche equilibrium', both types of S have quiche for breakfast and R replies F to B and D to Q. The first equilibrium is rationalized by out-of-equilibrium beliefs $\mu(W/Q) \geq 1/2$. The second by $\mu(W/B) \geq 1/2$ ¹².

It is straightforward to see that the 'quiche equilibrium' is not stable, it fails *divinity* and the Intuitive Criterion. To see why it is not stable, note that, in the 'quiche equilibrium', drinking beer is never a weak best response for the weak type and therefore can be eliminated. Deleting the possibility for the weak type to drink beer causes D to be dominated by F. Thus by **P2** the 'quiche equilibrium' is not stable. Moreover, it is not *divine*. In fact, since in this equilibrium the tough type is more willing to defect than the weak type, the relative probability of tough should increase if the receiver observes beer. However, to support the 'quiche equilibrium' the receiver must believe that it is more likely that the weak type of sender has beer than the tough one. The 'quiche equilibrium' also fails the Intuitive Criterion. In fact, in this equilibrium, the weak type is getting its highest possible payoff and has no incentive to switch to drinking beer, regardless of how R would respond to

¹¹Here we are referring to a set-value solution. That is, each "equilibrium" is a set of equilibria differing for the out-of-equilibrium beliefs allowed.

¹²See Kreps (1990) for a discussion.

beer: that is $W \in J(B)$ ¹³. On the other hand, if the tough type could convince R of his type and thus induce him not to fight, he would obtain a higher payoff by switching to beer: $u_s^*(T) < u_s(T, B, D)$.

In the next section we present a model in which players update their beliefs following an adaptive rule; they choose a strategy (the sender a message and the receiver an action) that maximizes expected utility, given their beliefs, but sometimes make mistakes. By computer simulations it is shown that, in the perturbed system, the unique long run outcome is the 'beer equilibrium'.

3 The Model

Consider two populations of players: a population of *senders* and a population of *receivers*. Let N be the number of individuals in each population, $v(W)$ be the number of weak individuals in the population of senders and $w = v(W)/N$ ($w < 1/2$).

Imagine that the basic game is repeated T times (T large) and in every period τ each sender is randomly matched with a receiver who does not know the sender's type but knows the proportion of weak individuals in the population of senders.

We make the following assumptions on players' behaviour:

A1: *All individuals in a population share the same beliefs.* ¹⁴ Let $p_1(\tau)$ be the receiver's belief at time τ that the sender is weak given that he has chosen beer; $p_2(\tau)$ be the receiver's belief at time τ that the sender is weak given that he has chosen quiche; $p_3(\tau)$ be the sender's belief at time τ that the receiver responds fight to beer; $p_4(\tau)$ be the sender's belief at time τ that the receiver responds fight to quiche.

A2: *At any time τ , given $p_3(\tau)$ and $p_4(\tau)$ and knowing his own type, each sender chooses beer or quiche so as to maximize his current expected utility.*

A3: *At any time τ , given $p_1(\tau)$ and $p_2(\tau)$ and having received a message $m \in \{B, Q\}$ from his matched opponent, each receiver chooses F or D so as to maximize his current expected utility, given beliefs about the opponent's type.*

A4: *With a given probability p each player makes a mistake and chooses randomly between the actions at his disposal and according to a probability*

¹³Recall that $J(B)$ is the set of types who get less than their equilibrium payoff by choosing the out-of-equilibrium breakfast B .

¹⁴This captures the idea that all individuals in a population share the same information, either because each individual observes the outcome of every game played, or because society keeps records of what happens. More troublesome is the implicit assumption that all individuals in a population share the same prior.

distribution that puts equal weight on each alternative ¹⁵.

A5: At the end of each period populations' beliefs are updated according to the following rule:

$$p_i(\tau+1) = (1-\lambda(m))p_i(\tau) + \lambda(m) \frac{v(m, h(i))}{v(m)} \quad i=1,2,3,4.$$

where $m \in \{B, Q\}$; $v(m)$ is the number of times that the message m has been observed; $\lambda(m) = \lambda v(m)/N$, $0 \leq \lambda \leq 1$; $v(m, h(i))$ is the number of times that $\{m$ and $h(i)\}$ has been observed, $h(i)=W$ for $i=1,2$ and $h(i)=F$ for $i=3,4$. According to this rule beliefs are updated using new information: current beliefs are a weighted average of previous period's beliefs and observed frequencies, with weights $1-\lambda(m)$ and $\lambda(m)$ respectively. If $\lambda=0$ then beliefs are static, that is to say, they do not change with new information; if $\lambda=1$ then beliefs are solely determined by the behaviour observed in the previous period (no memory of the past).

4 Simulations' Results

We consider the model with $w=0.2$, $T=2,000$ and $\lambda=0.1$ ¹⁶ In the model without mistakes both sequential equilibria have a basin of attraction and the long run outcome depends on initial beliefs. The dynamics of players' beliefs is shown in figures 1 to 3 for different initial conditions. In figure 1 initial beliefs are (.9, .1, .9, .1). After few repetitions the system settles at beliefs (.9, .2, .9, 0) which are consistent with the 'quiche equilibrium' ¹⁷. In fact, as can be seen in table 1, for the given initial beliefs the only actions ever observed are "quiche" for breakfast and "do not fight" as reply. Thus, since no observation intervenes to modify p_1 and p_3 they remain at their initial value. With initial beliefs (.1, .9, .1, .9) and (.5, .5, .5, .5) the system quickly

¹⁵The idea that players sometimes make mistakes is clearly at odds with the interpretation that deviations from the equilibrium are due to conscious signaling or experimentation, as in Fudenberg-Kreps (1988). If an "unexpected" message is interpreted as a mistake then it contains no information about the sender's type.

¹⁶In the simulations we have tried $N=10$ (thus $v(W)=2$) and $N=100$ (thus $v(W)=20$) obtaining the same results.

¹⁷The 'quiche equilibrium' is characterized by $p_2=w$, $p_4=0$ and arbitrary p_1 and p_3 can take any value. Analogously, the 'beer equilibrium' is characterized by $p_1=w$, $p_3=0$ and arbitrary p_2 and p_4 .

converges to the 'beer equilibrium' (see table 1). The patterns of beliefs for these initial conditions are shown in figures 2 and 3, respectively. The comparison between figures 2 and 3 and table 1 confirms that out-of-equilibrium beliefs can be arbitrary (in figure 2 $p_2=p_4=.9$ while in figure 3 $p_2=p_4=.5$).

The introduction of mistakes by players greatly changes the dynamics of beliefs. With mistakes, every action has positive probability of being taken (and observed); therefore, $p_i > 0 \forall i$. As it is shown in figures 4, 5 and 6, the introduction of mistakes leads the system "close" to the 'beer equilibrium' for any initial distribution of beliefs (figures 4, 5 and 6 are obtained for the same initial conditions as figures 1, 2 and 3, respectively, but for a probability of mistake $p=.1$). Table 1 shows that, even if players' beliefs cycle, their actions are, most of the time, close to the 'beer equilibrium'. A comparison of figures 6, 7 and 8 suggests that the length of the cycle in players' beliefs depends on the probability of mistake: the smaller is p the longer is the cycle. This is because with smaller p it takes longer for a given change in beliefs to occur (in the limit when $p=0$ no change in beliefs occurs). Note that, while changing, players' beliefs remain such that no player has an incentive to deviate from the equilibrium, which is thus observed most of the time ¹⁸.

Changing λ does not affect the long run results but it affects the length of time in which the system is influenced by the initial conditions (with $\lambda=.001$ and $p=.1$ it takes about 30.000 repetitions before the 'beer equilibrium' is played) and the length of the cycle in players' beliefs.

Changing the proportion of weak individuals in the population does not change significantly the results as far as this number is not greater than $N/2$ ¹⁹.

5 Conclusions

In this paper we have shown, with an example, that in signaling games adaptive learning can lead players to play according to a (sequential) equilibrium; moreover, by adding mistakes the learning dynamics provides an equilibrium selection device. Along the lines of Young (1993) we interpret this

¹⁸ $p_4 > p_3 + 1/2$ ensures that $u_S(W, B, p_3, p_4) > u_S(W, Q, p_3, p_4)$;
 $p_1 < 1/2$ ensures that $\sum_{t \in T} u_R(t, B, D) \mu(t/B) > \sum_{t \in T} u_R(t, B, F) \mu(t/B)$ where $\mu(W/B) = p_1$;
 $p_2 > 1/2$ ensures that $\sum_{t \in T} u_R(t, Q, F) \mu(t/Q) > \sum_{t \in T} u_R(t, Q, D) \mu(t/Q)$ where $\mu(W/Q) = p_2$.

¹⁹ When $w > 1/2$, the unique sequential equilibrium is beer for the tough sender, the mixed strategy $((1-w)/w; (2w-1)/w)$ for the weak sender and the mixed strategy $(.5, .5)$ if beer and fight if quiche for the receiver.

last result as an indication that the 'beer equilibrium' is the easier to get into "by mistake"; in fact, the tough sender is easily convinced to drink beer if he observes the (out-of-equilibrium) response F to quiche. Note that since the game is not weakly acyclic according to Young's (1993) definition,²⁰ his results are not directly applicable here.

As compared to Fudenberg-Kreps (1988), which seem to need sophisticated experimentation, our example suggests that naive experimentation (mistakes) may be enough to rule out *unplausible* (sequential) equilibria in signaling games.

²⁰In fact, the Nash equilibria of the strategic form are not strict.

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Table 1*: $w=0.2$, $T=20,000$, $\lambda=0.1$.

Initial beliefs	p	WB	WQ	TB	TQ	BF	BD	QF	QD
.9 .1 .9 .1	0	0	.2	0	.8	0	0	0	1
.1 .9 .1 .9	0	.2	0	.8	0	0	1	0	0
.5 .5 .5 .5	0	.2	0	.8	0	0	1	0	0
.9 .1 .9 .1	.1	.1	.1	.7	.1	0	.8	0	.1
.1 .9 .1 .9	.1	.2	0	.8	0	0	.9	0	0
.5 .5 .5 .5	.1	.2	0	.8	0	0	.9	0	0
.5 .5 .5 .5	.05	.2	0	.8	0	0	.9	0	0
.5 .5 .5 .5	.025	.2	0	.8	0	0	1	0	0

*Values are approximated to the first decimal place.

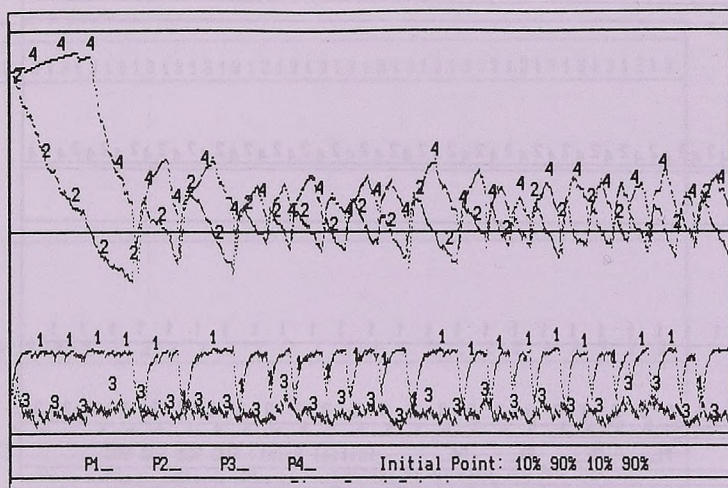


Fig.5 initial point (.1, .9, .1, .9) $p=.1$

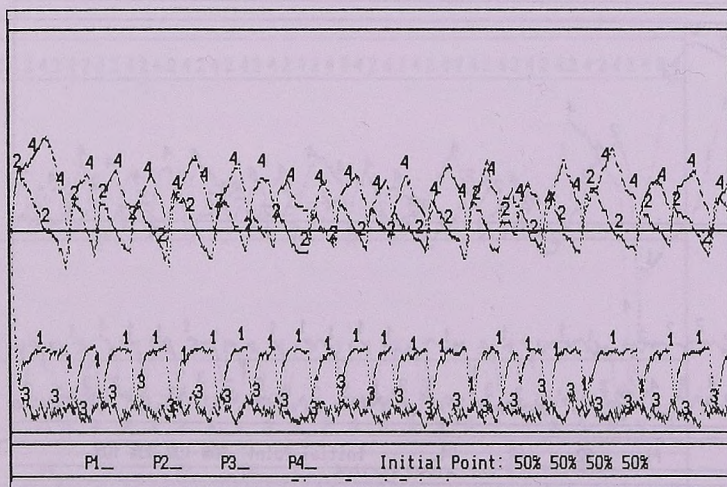


Fig.6 initial point: (.5, .5, .5, .5) $p=.1$

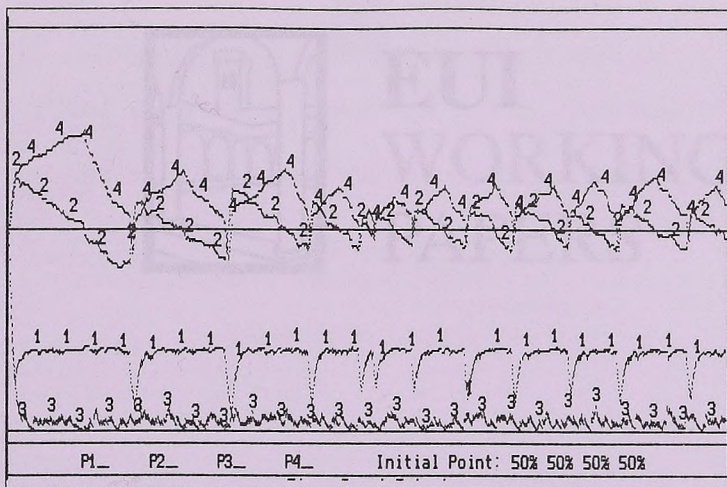


Fig.7 initial point (.5, .5, .5, .5) $p=.05$

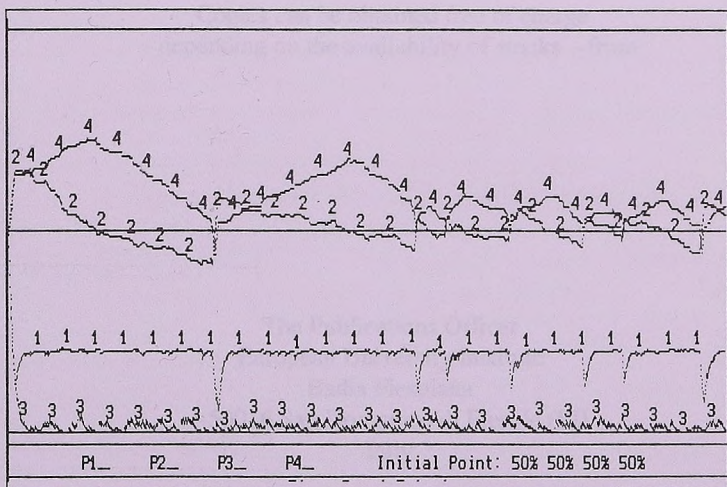


Fig.8 initial point (.5, .5, .5, .5) $p=.025$



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